

Micro-generation technology assessment for housing technology

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Abstract

Micro-generation is defined as a notion of simultaneous generation of both heat and power in an individual dwelling. It offers an elegant and economically viable way to meet the residential power/thermal loads and Kyoto targets by demonstrating superior environmental performance with high efficiency and low harmful greenhouse gas emissions. However, before introducing micro-generation systems in large quantities a number of issues should be resolved in terms of system integration, interconnect, reliability and safety.

Two demonstration houses were built at the Canadian Centre for Housing Technology that have the capability of assessing different energy and building technologies under real-life conditions. A project was initiated involving a consortia of Canadian electric and gas utilities, Canadian Government agencies and Canadian fuel cell manufacturers to modify one of two existing research houses and to integrate a prototype micro-generation unit in it that would provide electricity and heat to the house, and supply surplus electricity back to the grid. The key research objectives were assessment of building integration, micro-generation system design issues and system performance characteristics. A Stirling engine micro-generation unit, fuelled by natural gas, was used for this demonstration. The unit had an electrical output of 736 W_e and a thermal output of 6.5 kW_{th}. The Stirling engine was connected in parallel to the grid and the residual heat from the engine was utilized through a specifically designed heat utilization module.

The paper discusses the micro-generation system performance in two different setups and scenarios that were tested over the 2003 winter/spring seasons. Data showed that the micro-generation unit was able to satisfy all of the space and water heating loads to the house during the testing period. The unit provided a considerable percentage of the house's electrical requirement, and even exported, in a few instances, some electricity back to the grid.

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1. Introduction

Small combined heat and power (CHP) systems that can generate thermal and electrical energy at a community or even single household level are beginning to emerge as a viable alternative to large and expensive central power generating stations. The 1998 Ice Storm in eastern Canada, rolling brownouts in California, and the recent 2003 blackouts in eastern North America and Europe, have increased public interest in small power generation systems that can provide primary or back-up power for dwellings. These systems are even more attractive for remote communities where lack of central generation stations and costly connection to the grid is neither an affordable nor a preferable option.

Micro-generation is defined as a notion of simultaneous generation of both heat and power in an individual dwelling on site. It is also known as micro-combined heat and power generation. Despite some similarities, there is a significant difference in the way a micro-CHP system operates compared to the well-known CHP systems, both in terms of technology and economical issues and social and environmental constraints imposed on it. Micro-CHP offers an elegant and economically viable way to meet the residential power and thermal needs and Kyoto targets, by demonstrating superior environmental performance with high efficiency and low harmful greenhouse gas emissions. However, the introduction of micro-generation will significantly change the way the utilities and homeowners see their partnerships and joint effort to meet the load/demand. The electricity grid in this new environment is seen not as a primary power supplier but instead as a back-up of the micro-CHP system. "Talking"

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between the micro-CHP and the grid in most instances will be done simultaneously, governed by the power and heat demand from both sides of the equation. Importing power from, and exporting power to the grid will be a daily reality. However, before introducing micro-CHP technologies in large numbers, groundwork should be laid out in terms of system integration, interconnect, system reliability and safety issues.

There are several technologies being developed for micro-generation. The most promising clean-fuel CHP technologies are Stirling engines (SE) and fuel cells (FC). While fuel cells are the most attractive, due to their undisputed advantages as power generators they are still in the development stage and will take some time until they are introduced to the market. Residential Stirling engines in the meantime appear to be closest to commercialization and the developers have realized the significant opportunities they offer as CHP systems in residential market. Micro-generation CHP systems such as fuel cells, Stirling engine, internal combustion engine, etc., in size of 1–10 kW_e would be able to provide all or part of the power and heat load required by a typical household. Most of the systems will be suitable for both off-grid and grid-connected applications. In either case, heat produced during the electricity generation can be recovered and used to satisfy space and water heating of the house in winter and to provide thermal cooling during the summer season.

Two demonstration research houses were built at the Canadian Centre for Housing Technology (CCHT) that have the capability of assessing different energy and building technologies under real-life conditions. A project was taken by a consortia of Canadian electric and gas utilities, Canadian Government agencies, and a Canadian fuel cell manufacturers to adapt one of two existing research houses and to integrate a prototype micro-generation unit that would provide electricity and heat to the house, and supply surplus electricity back to the grid. The key research objectives were assessment of building integration, micro-generation system design issues and performance characteristics.

Modifications were made to the power layout, the mechanical and monitoring systems of the CCHT Test House to allow quick connection of the residential micro-CHP systems with detailed monitoring of all essential electrical and thermal micro-CHP quantities.

2. CCHT houses

The Canadian Centre for Housing Technology's research facility consists of two identical research houses—the *reference house* and the *test house* as shown in Fig. 1. These were built to the R-2000 standard and feature identical simulated occupancies. The houses have been calibrated and are very nearly identical. They are monitored with high accuracy for energy performance and thermal comfort. The *test house* is usually used for installation of innovative energy saving components or systems that are being assessed. The



Fig. 1. Twin research houses.

resulting change in performance is documented relative to the benchmark configuration in reference house [1,2].

- *Reference house*

The *reference house* is a typical two-storey wood-frame house, with 210 m² livable area. It is built with a poured-in-place concrete basement, and with style and finish representative of current houses available on the local housing market. It meets the R-2000 Standard while having a standard '2 × 6' wall. It has a high efficiency sealed combustion condensing gas furnace, a power-vented conventional hot water heater and a heat recovery ventilator, along with a number of well-insulated and tight assemblies to complete the R-2000 package.

- *Test house*

The test house was initially identical to the *reference house*, but was modified to incorporate the micro-CHP system. In the assessment, the *test house* is shown to be very nearly identical to the reference house from the point of view of energy performance. This performance comparison forms the benchmark against which other technologies can be compared. The *test house* is then modified to assess the impact of innovative energy systems and components on the overall energy and comfort performance of the house. The *test house* is used to assess only one component at a time, on a week-by-week basis. On completion of the assessments, the *test house* was returned to its starting (benchmark) configuration and the benchmark was re-confirmed. Selected characteristics of the house are reported in Table 1.

Simulated occupancy controls. The houses are equipped with sophisticated control equipment similar to home-automation technologies, which operate lighting, plumbing and major appliances (stove, washer, dryer, and dishwasher). Generating the equivalent amount of heat with lamps simulates heat release associated with occupant presence and the operation of small appliances. The system features a combination of off-the-shelf automation control modules,

Table 1
Selected characteristics of the houses

Component	Characteristic
Construction standard	R-2000
Storeys	2
Livable area	210 m ²
Basement	Poured concrete, full basement
Garage	Two-car, recessed into the floor plan; isolated control room in the garage
Attic	RSI 8.6
Walls	RSI 3.5
Rim joists	RSI 3.5
Exposed floor over the garage	RSI 4.4 with heated/cooled plenum air space between insulation and sub-floor
Basement walls	RSI 3.5 in a framed wall. No vapor barrier
Basement floor	Concrete slab, no insulation
Windows	Low-e, insulated spacer, argon filled, with argon concentration measured to 95%
Window area	South facing: 16.2 m ² , total: 35.0 m ²
Air barrier system	Exterior, taped fiberboard sheathing with laminated weather resistant barrier. Taped penetrations, including windows
Airtightness	Reference 1.07 ach at 50 Pa; test house 0.97 ach at 50 Pa
Heat recovery ventilator	High efficiency (84% nominal)
Furnace	Condensing gas at 91% efficiency (as measured)
Hot water heater	Conventional, induced draft at 67% efficiency (as measured)
Air conditioning	High efficiency, SEER 12 (nominal)

and some unique custom adaptations. The simulated occupancy system is identical and synchronized in both houses. A target of 20 kWh per day of electricity consumption was set, which corresponds to an accepted standard used for modeling energy systems in houses [3,6].

3. Design modifications and control strategy

The design changes and modifications implemented to the facility to accommodate the micro-CHP system were as follows.

3.1. Electrical modifications to integrate the CHP system into the house's electrical system

The modifications were made to accommodate the installation of combined heat and power systems having a generating capacity up to 40 kW_e, for either grid-dependent operation or stand-alone, grid-independent operation [7].

The following wiring changes were made to each¹ test house:

- Three additional bi-directional, pulse generating kilowatt-hour meters, and an additional power quality meter were added for monitoring purposes.
- A weatherproof, padlockable disconnect switch was installed on the exterior of each house to meet requirements of rule 84-028 of the Canadian Electrical Code.

- A four-pole transfer switch was installed to allow various generator configurations without re-wiring.
- A 100 A disconnect/isolating switch with 20 A fuses was installed to protect and isolate the CHP generator under test.

A schematic diagram of the integration of these elements to the test house is shown in Fig. 2.

3.2. Stirling engine

The micro-generation technology used during the project was a personal power station providing heat and electricity in cogeneration mode of operation. Based on closed thermodynamic Stirling cycle the engine was able to generate 736 W_e of electricity and 6.5 kW_{th} of heat. The working

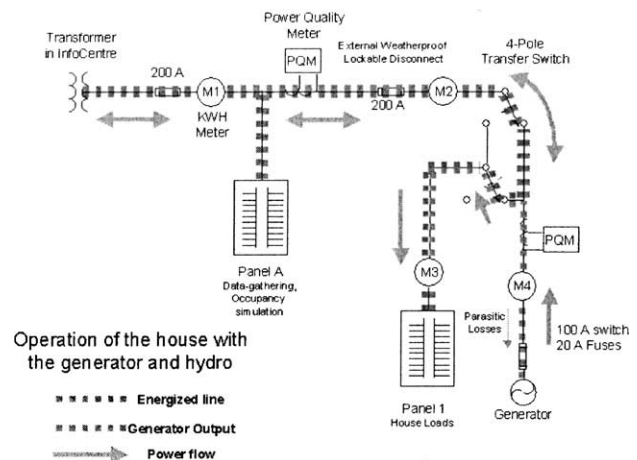


Fig. 2. Schematic diagram of the upgraded wiring and metering in the CCHT houses.

¹ Both the reference and test houses at CCHT were upgraded according to the wiring diagram in Fig. 2. The test house was the focus of this project, because the CHP unit was installed in that house.

nitrogen gas is repeatedly heated and cooled as the gas pressure causes the pistons to move up and down and via a mechanical means rotate an alternator to generate electricity. Heat from the flue gases and the engine cooling system is recovered as hot water and utilized through a thermal utilization module. The electricity generated is used either to satisfy the house load or sent back to the grid.

3.3. Balance of plant design and installation

The SE is a thermally driven engine, and the overall performance of the micro-CHP system depends greatly on the efficient residual heat utilization through the balance of plant (BOP). For the purposes of the project the existing integrated gas-fired space and water heating system (ISWHS) already in the house was upgraded with additional means of thermal storage and connected to the micro-CHP unit as shown in Fig. 3. The ISWHS was already hooked-up to the house, providing domestic hot water and space heating on demand [2]. The burner of the ISWHS was used as a back-up or supplemental burner in instances where the CHP unit could not supply all of the heat requirements, either due to heavy demand or shutdown of the CHP unit. The BOP components were configured in two different ways to investigate whether the strategy for directing heated water and cooler return water had an impact on the operating and overall efficiencies:

- *Setup 1.* The storage tank (ST) is used as a supplementary heater to the hot water tank (HWT), warm water in storage circulated to HWT, and cooler HWT water back to storage. HWT gets the fresh water supply as shown in Fig. 3.
- *Setup 2.* ST is in series with the HWT, hot water from the hot water storage tank circulated to HWT and then to space heat load and back to ST, or to water heating, with fresh water into ST.

In both configurations, the CHP unit is the heating source to the storage, with a closed loop and heat exchangers linking the CHP unit to the storage.

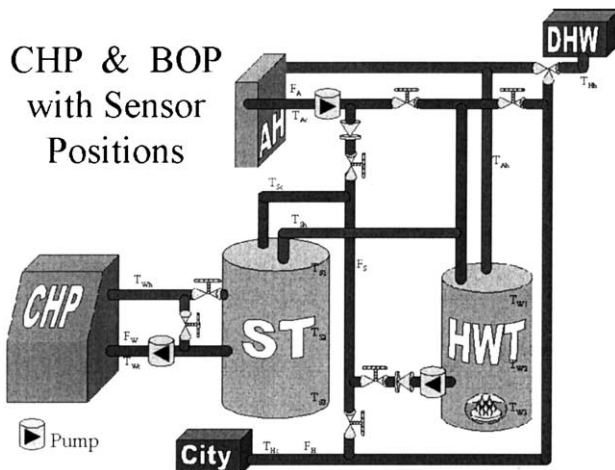


Fig. 3. Schematic diagram of the balance of plant and sensors.

3.4. Control strategy

The SE is designed as a heat-driven device and its operation is controlled by the thermal status of the BOP. The BOP control can be done through sophisticated artificial intelligence (AI) control strategies [4,5] or through a simple means utilizing the existing controls and information from a few additional sensors. A second approach was applied as the CHP unit and the pump are turned on if the CHP is in standby mode and the temperature of the top of the ST is $<60^{\circ}\text{C}$. The CHP unit is turned off if outgoing temperature is $>80^{\circ}\text{C}$. The CHP circulation pump is turned off 25 min after the CHP unit is turned off. The developed BOP control strategy manages the temperature in the thermal storage tanks by turning on and off circulation pumps according to aquastat readings and the temperature differential between the top and bottom of the thermal storage. The house thermostat controls the operation of the water pump and the air handler (AH) unit.

4. Test results

The evaluation of the micro-generation system took place in winter/spring 2003. For analysis purposes, the overall monitoring period was split up into individual ‘runs’ for which energy balances and system efficiencies were calculated. In essence, each ‘run’ can be viewed as an individual experiment.

As was expected, both the SE and the balance of plant performance were heavily dependent on the thermal load of the system. Some of the trends emerging from this analysis are described below.

4.1. CHP unit efficiency

The CHP unit efficiency increased only slightly with an increase in the thermal load. When there was no demand for space heat (hot water demand only), the average demand on the BOP was 0.48 kW. The curves in Fig. 4 are projected to reach close to the CHP unit output capacity of 6.5 kW. At 75% BOP efficiency, that is 4.88 kW of delivered heat. According to the statistical analysis the CHP unit heating efficiency varied from 74% for hot water only to about 79% at system capacity and the CHP unit electrical efficiency varied from 5.5 to about 9% at system capacity. The CHP unit’s total efficiency varied from 79.5% for hot water only to about 88% at system capacity (Table 2).

4.2. BOP and system efficiency

The energy efficiencies of both the BOP and the total system show significant dependence on thermal load. This is due to the fact that the stand-by losses from the BOP are relatively constant, while the useful heat varies mainly with space heat load. The BOP efficiency varies from 47.6%

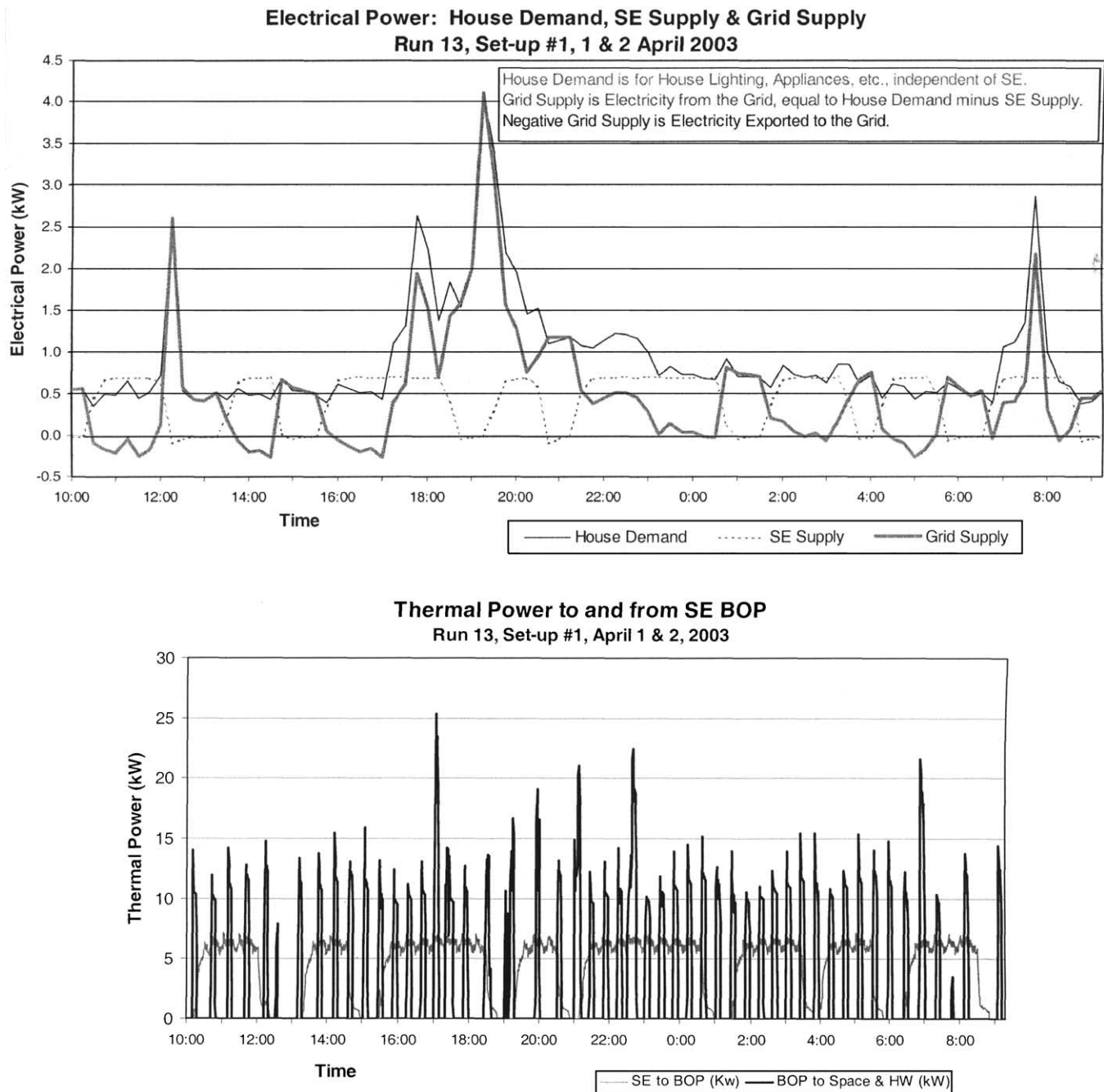


Fig. 4. Power and thermal demand/load profiles.

for hot water only to nearly 80% at CFIP capacity, and the system efficiency varies from 41% for hot water only to over 70% at CHP capacity (Table 3).

4.3. Results by setup configuration

There were only small differences between the two setups being investigated. It appears that setup 2 generated a slightly better electrical efficiency compare to setup 1. Analysis of each setup for dependence on the BOP thermal

output showed little appreciable difference in the sensitivity of the setup to that factor.

4.4. Role of thermal storage interfacing between CHP and air handler

The thermal storage of the BOP receives heat from the CHP unit over longer periods but in small quantities, and delivers that heat to the air handler and hot water devices in shorter but more heat-intensive bursts. It is these

Table 2
CHP unit efficiencies

Run	Setup	Heat (%)	Electric (%)	Total (%)
1	1	80.5	8.3	88.7
2	2	79.6	8.0	87.5
3	2	75.0	9.0	83.9
4	2	76.1	6.7	82.8
7	2	74.7	7.2	81.8
8	2	75.3	7.0	82.3
9	2	75.2	7.3	82.5
11	1	76.4	7.5	83.9
13	1	77.1	7.7	84.9
20	1	77.9	6.4	84.4
21	1	74.2	5.9	80.1
22	1	74.0	5.8	79.7
23	2	77.1	6.7	83.8
24	2	75.6	6.4	82.0
25	2	73.1	6.3	79.4
26	2	74.6	6.2	80.7
27	2	75.5	6.1	81.6
28	1	75.8	5.8	81.6
29	1	78.1	4.8	78.1
31	1	75.7	4.3	80.0
33	1	74.1	5.8	79.9
34	1	74.1	5.3	79.4
35	2	73.5	5.5	78.9
36	2	74.3	6.5	80.7
37	2	74.0	4.0	78.0
38	2	74.3	8.1	82.4
39	2	73.4	4.0	77.5
Minimum		73.1	4.0	77.5
Mean		75.5	6.4	81.7
Maximum		80.5	9.0	88.7
Mean, setup 1		76.2	6.1	81.9
Mean, setup 2		75.1	6.6	81.6

characteristics that highlight the importance of the storage design. An optimized storage system should be able to stretch the operation of the CHP unit into even longer runs, reducing standby heat losses, while satisfying the air handler's and hot water system's needs for energy on their own demand schedules.

5. Discussion

This project successfully adapted one of two existing research houses at CCHT to integrate a prototype CHP unit to provide electricity and heat to the house, and supply surplus electricity back to the grid [7]. The adaptation consisted of electrical modifications to incorporate a CHP unit to the electrical system, including added wiring, safety switches, electrical panels and power quality meters. Thermal modifications including added components of the BOP were integrated with an existing integrated space and water heating system.

Some of the issues addressed but not necessarily resolved over the course of the study included:

Table 3
Balance of plant and total system efficiencies

Run	Setup	BQP (%)	System (%)
1	1	71.6	66.3
2	2	72.2	66.1
3	2	51.7	48.9
4	2	55.4	49.6
7	2	62.7	55.1
8	2	66.2	58.1
9	2	66.1	58.1
11	1	70.5	62.3
13	1	75.1	66.4
20	1	68.2	60.0
21	1	50.3	43.4
22	1	53.2	45.3
23	2	67.5	59.0
24	2	61.8	53.2
25	2	50.3	43.3
26	2	50.9	44.9
27	2	61.1	52.4
28	1	53.8	46.7
29	1	46.8	39.9
31	1	46.3	39.7
33	1	51.2	44.1
34	1	44.9	38.9
35	2	44.2	39.1
36	2	44.8	39.8
37	2	47.4	39.3
38	2	45.9	42.3
39	2	53.6	43.5
Minimum		44.2	38.9
Mean		56.8	49.8
Maximum		75.1	66.4
Mean, setup 1		57.4	50.3
Mean, setup 2		56.4	49.5

- The variability in acceptance by local utilities of the concept of feeding electricity back to the grid on a micro-level.
- The need by the Canadian Electrical Code for an external, weatherproof, lockable disconnect switch to allow the power utility to manually disconnect the CHP from the grid during periods of power failure and repair.
- The optimization of the balance of plant (for heat storage and distribution) to minimize shutdown of the CHP, and maximize the overall efficiency of the thermal part of the system.
- The role of a heat-driven CHP unit in the summer, when the thermal load is small and the BOP heat losses to the house are relatively high.

6. Conclusions

The performance of a residential Stirling engine-based CHP system was quantified and building integration issues such as HVAC interface, thermal storage, control, and CHP system sizing were examined. The electrical and thermal installations at the CCHT test house were modified, and

combined monitoring and data analysis techniques were developed. The efficiencies of the CHP unit, the BOP, and the overall system were all quantified for a range of conditions, and good functional relationships were developed that describe the performance of this system over a broad range of conditions. The complementary analytic techniques and mathematical models developed over the course of the study emphasized the importance of system sizing and storage [7]. Both these factors were shown to have a significant effect on duty cycle and standby times, the latter being identified as a major component of the BOP inefficiency. The project showed the capability of the CCHT research houses to test a range of micro-generation combined heat and power systems in a residential application. It also clearly demonstrated the advantage of pre-field trials under control conditions for delivering useful information about the micro-CHP performance and integration of related sub-systems.

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